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# ASSESSMENT OF THE POTENTIAL FOR DATING SECONDARY CALCITE AND QUARTZ IN FAULT ZONES

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RESEARCH REPORT

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## FOREWORD

The objective of this report is to determine through a literature review, whether or not there are any techniques which are presently capable of, or are likely to become available for, directly dating quartz and calcite crystals, which are at least tens of millions of years old.

Currently employed dating techniques, both isotopic and physical, have been carefully reviewed. Because of the chemical compositions and atomic structures of calcite and quartz, the emphasis was changed to the physical techiques.

The physical techniques, thermoluminescence, thermally stimulated current and electron spin resonance were carefully evaluated. Thermoluminescence, in particular, during the last decade, has become a well established dating technique in archaeometry. A short section on pressure indicators is also included.

The conclusions and recommendations are based on published information.

## ABSTRACT

Calcite and quartz occur frequently as secondary minerals in faults. In many instances these minerals are not deformed, calcite for example often exhibits an undisturbed fibrous habit or appears as euhedral crystals. Direct dating of euhedral, or well formed crystals would provide a minimum age of the last movement along a fault whereas dating of fibrous crystals would furnish the real age of the last movement. This information would be essential in the evaluation and selection of sites for both nuclear power reactors and nuclear waste disposal. In the Canadian context, to be successful, the technique should be able date minerals as old as tens of millions of years.

In this study both isotopic and radioactive damage techniques were considered. It was found that individually, thermoluminescence, thermally stimulated current and electron spin resonance offer possibilities. Recent electron spin resonance studies of ancient flints have yielded dates of several hundred million years. It is anticipated that in the near future a combination of the above techniques will be extensively used in the field of geochronology.

## Résumé

La calcite et le quartz sont retrouvés fréquemment comme minéraux secondaires dans les failles. Très souvent ces minéraux ne sont pas déformés; ainsi la calcite par exemple peut apparaître sous un habitus fibreux non déformé ou en cristaux automorphes. La datation absolue effectuée sur les cristaux automorphes bien formés donnerait l'âge minimum pour les derniers mouvements de la faille tandis que la datation absolue effectuée sur les cristaux fibreux révèlerait l'âge véritable des derniers mouvements ou des dernières déformations. Cette information s'avère essentielle dans l'évaluation et la sélection d'emplacements pour les centrales thermonucléaires ou pour l'élimination des déchets radioactifs. Dans le contexte du Bouclier Canadien les techniques doivent pouvoir dater des minéraux de plusieurs dizaines de millions d'années.

Les techniques isotopiques et celles basées sur les dommages radioactifs ont été considérées dans cette étude. Prise séparément, la thermoluminescence (TL), la réaction électrique a une excitation thermique (TSC) et la résonance électronique magnétique (ESR) offre des possibilités. Des travaux récents sur la résonance électronique magnétique des "silex" anciens ont donné des dates de plusieurs millions d'années. A court terme, il est à prévoir qu'une approche globale utilisant toutes ces méthodes basées sur les dommages radioactifs va être plus couramment utilisée en géochronologie.

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# 1- INTRODUCTION

The objective of this study is to determine if there are any techniques which are presently capable of, or may become available for, dating quartz and calcite crystals which are several tens of millions of years old.

In site selection for a nuclear reactor or a nuclear waste repository, if a fault has been identified, it is important to determine, as accurately as possible, the date of last movement in order to evaluate whether or not the fault is likely to be reactivated. In many instances, when secondary minerals are present as euhedral, or well formed crystals a minimum age for the last movement could be obtained if a suitable dating technique could yield an absolute age for the secondary minerals. If the texture of the secondary minerals show no physical evidence of deformation the minerals are therefore post-deformation. Knowledge of their age of formation would indicate the true span of time during which no movement has occurred along the structural lineament.

To date, the techniques available for absolute dating of minerals and rocks can be divided into two major categories:

## 1.1- Isotopic Techniques

These techniques are presently the most widely used in geochronology. The radioactive clock is based on the constant disintegration of natural radioactive elements. The age is obtained by measuring the parent/daughter ratio. The disintegration is not affected by

the pressure, temperature conditions experienced at the surface of the earth. Some of the best known techniques are:

- potassium - argon (K - Ar)
- rubidium - strontium (Rb - Sr)
- samarium - neodynium (Sm - Nd)
- uranium - lead (U - Pb)

For most minerals and rocks, the isotopic techniques are the only ones presently capable, of routinely dating, with precision, a span of time in the range of tens of millions of years. Certain techniques are more applicable than others, for a given mineral or rock. The limitations of each technique are related to the chemistry and structure of the mineral or rock under consideration.

1.2 - Radioactive Damage Technique or Physical Techniques

Radioactive damage techniques or physical techniques are not as widely known as the isotopic techniques but thermoluminescence, (TL), has been used extensively in the past decade, in archeometry for dating pottery and other artifacts (Aitken 1972). Besides thermoluminescence the other physical techniques considered in this report are; thermally stimulated current TSC, electron spin resonance ESR or EPR and fission track. The above mentioned techniques, with the exception of fission track, are based on the accumulation of electronic charges in the crystal lattice of the minerals with time. These charges originate from a constant ionization radiation flux coming from the radioactive decay of natural elements. The basic principles

used in age determination by either (TL), TSC or ESR are essentially the same, they differ only in the measurement of the electronic charge population. Contrary to the isotopic techniques, the radioactive techniques are very sensitive to pressure and temperature condition.

Of interest in the study, is the dependence of thermoluminescence on pressure which has been used in the past to evaluate the strain conditions in, or surrounding, faults. The stress-strain conditions are reflected qualitatively by changes in the shape or the intensity of the signal (Morency 1973). These changes occur before noticeable deformation can be identified under microscope or by strain gauges. Triboluminescence is another phenomenon which is related to failure or micro-fracturing and can be considered, with (TL) as a pressure indicator used to monitor a faulted rock mass (Lahav 1981).

Since the early fifties, thermoluminescence and fission track were the best known and most widely used of the radioactive damage techniques. More recently (ESR) has been applied succesfully in dating apatite, calcite and quartz. In a recent study of flint (quartz), the span of time to which this radioactive technique could be applied was substantially extended (Garrison 1981).

## 2- ISOTOPIC TECHNIQUES

The parent daughter initial ratio is the main prerequisite for the successful age determination of a mineral and/or rock by an isotopic technique. The initial ratio must be such that it will eventually yield a parent daughter ratio that can be accurately measured with a mass spectrometer. Qualitatively, this implies that the initial abundance of the parent is sufficient to produce measurable radiogenic daughter and still remain abundant. On the other hand, the initial daughter concentration should be low in order to measure small increment of the radiogenic daughter.

### 2.1- Potassium Argon (K-Ar), Rubidium Strontium (Rb-Sr)

In unpublished reports for nuclear agnecies, cases are found whereby the (K-Ar) or (Rb-Sr) have been used in an attempt to date zeolites and mylonite found in faults (Robbins 1978). Potassium argon dates on zeolites always yielded younger ages compared with ages inferred from geological evidences. The problem is related to important loss of radiogenic argon from the structure and even the application of the $^{39}Ar/^{40}Ar$ technique does not solve the problem. The (Rb/Sr) technique was also tried on the zeolites samples. It defined a straight line with a negative slope that could not be explained by the radioactive decay of Rb to Sr (Odom 1979).

Another case was reported where an age was obtained by Rb/Sr for a mylonite containing quartz and feldspars; in that particular instance, it was possible to define an isochron which yielded an age

(Odom 1979). In the Canadian shield context, the above cases could be applied in rare occasions. Field observations indicate that calcite and quartz are the most common secondary materials found in faults. Neither mineral can be dated by these techniques because the parent daughter initial ratio prevents direct dating by isochron technique or from calculated isotopic dates.

## 2.2.- Disequilibrium Series ($^{230}Th/^{234}U$)

There are several, somewhat different methods of using the uranium series for age dating. For example, travertine samples have been dated using $^{230}Th/^{234}U$ disequilibrium series. The technique is directly applicable to calcite precipitating from water solution, but could be applied to relatively young calcite of other origins if suitable uranium concentrations could be found (Kaufman 1971). This method would be applicable to ages in the range of 50,000 - 350,000 years (Hedges 1979), but it is doubtful that it could be extented much beyond.

Quartz does not readily accept uranium and thorium into its lattice which would prevent the application of the uranium disequilibrium technique to that mineral.

## 2.3- Samarium Neodynium (Sm-Nd)

The (Sm-Nd) technique is a recent addition to the isotopic techniques and its potential is still being evaluated. This technique offers the possibility of dating the entire rock spectrum including

the ultramafic rock which cannot be dated by other isotopic techniques. Both elements are "rare earths elements (R.E.E.) with odd mass numbers; $^{147}Sm$ decays by $\delta$ emission to $^{143}Nd$ (O'Nions 1977).

R.E.E. are present in p.p.m. in all minerals, but geochemical considerations indicate that this new technique will not be applicable to our particular problem for the following reasons:

- both elements have close relative natural abundance values of $^{147}$(Sm 14.97%) and $^{143}$(Nd 12.17%)
- both have close ionic radii Sm (1.00 Å) and Nd (1.04Å)
- both have a valence of + 3
- even if little is known for "rare earths elements" distribution in calcite and quartz of hydrothermal origin it is doubtful that the lattice of calcite and/or quartz could fractionnate efficiently the two elements bringing about a satisfactory parent/daughter ratio.
- the half life being extremely long with a value of $T\frac{1}{2}$ = ($1.08 \times 10^{-1}$ years). Unless the calcites are early Precambrian in age the ratio of the two elements could not be precisely measured with a mass spectrometer.

## 2.4- New Developments Using Particle Accelerators

The dating problem is seen in a new light when one realizes that for each decay/min. there may be as many as $10^9$ to $10^{12}$ or more radioactive atoms present. If we could measure the parent isotope before disintegration, the process would be more efficient.

Various particle accelerators can be used as conventional mass spectrometers. The former can accelerate ions to much higher energies (from kev to mev) increasing therefore the mass separation with interfering isotopes and increasing detection limits (Muller 1977).

In conventional techniques using a mass spectrometer dates can still be obtained after one to two half-lives have elapsed. Using the new techniques the limits could be pushed to 20 half-lives. The best illustration of this is found in the $^{14}C$ dating technique. The conventional approach had a maximum age limit of 40,000 years. In using a particle accelerator, ages greater than 100,000 years have been obtained. This new technique has also been applied to elements such as $^{10}Be$, $^{25}Al$, $^{53}Mn$, $^{81}Kr$, $^{205}Pb$ (Hedges 1979).

It remains doubtful that particle accelerators would be capable of measuring precisely the ratio of parents/daughters for their use in (K-Ar), (Rb-Sr) or (Sm-Nd) for calcite and quartz (Mose personal communication).

## 3- RADIOACTIVE DAMAGE TECHNIQUES (Physical Techniques)

### 3.1- Fission Track Dating

Fission track has been used successfully to date a wide variety of minerals and rocks in the range of 10 to 500 x $10^6$ years (Fleischer 1975). Most of the initial work was done on apatite and zircon found in granite. The fission track dates were then correlated with ages obtained by Rb-Sr and U-Pb.

Quartz and calcite have also been used for fission track dating (table 1), but only in rare cases have they successfully been dated by the technique. McDougall and Price (1974) found that tracks in calcite are annealed at ambient temperature (room temperature) with time which precludes the widespread use of calcite for fission track dating.

In the case of quartz, as stated previously, uranium is not easily accepted into its structure. Uranium is found mainly between grains or at the grain surfaces, and its concentration is also very low. Consequently fission track will be rare and could not be related to the age of the sample. Weiland (1979) has been the only one to successfully date quartz by fission track. In this particular case the quartz was in contact with urananite minerals and was used as an external detector or dosimeter to record the amount of spontaneous fission of $U^{238}$.

Table 1 Minerals and rocks used for fission track dating

| CRYSTALLINE MINERALS | AMORPHOUS MINERALS | ROCKS TYPES |
|---|---|---|
| Allanite | Amber | Adamellite |
| Anthophillite | Glasses * | Andesite |
| Apatite * | Archaeological | Ash * |
| Bastnasite | Basaltic | Basalt * |
| Calcite | Impact | Calcitic |
| Epidote | Man-made | Carbonatite * |
| Garnet | Obsidian | Clay |
| Hornblende | Shards | Diatremes |
| Micas * | | Diorite |
| Monazite | | Gabbro |
| Quartz | | Gneiss |
| Sphene * | | Granite * |
| Stibiotantalite | | Iron Ore |
| Tanzanite | | Kimberlite |
| Topaz | | Manganese crust |
| Zircon * | | Syenite |
| | | Tuff * |

(From Fleischer 1975)

* Most frequently dated

## 3.2- Thermoluminescence

### 3.2.1- Introduction

Thermoluminescence (TL) is the light emitted from minerals which when heated from room temperature to 400°C, yield a natural thermoluminescence (NTL) glow curve. A second heating will give a blank curve with incandescence appearing at temperatures in excess of 400°C. If the sample is then subjected to ionizing radiation an artificial thermoluminescence (ATL) glow curve can be obtained. Usually the (ATL) curve exhibits a greater number of peaks, especially at low temperatures, and a general increase in the light output over the entire temperature range (Figure 1). In an ideal and hypothetical case, a glow peak whether natural or artificial, represents electrons in defects with a corresponding trap depth "E" (Figure 2). The trap depth also represents a thermal release energy level for the electron. The thermal release energy is measured with relation to the bottom of the conduction band. In general the greater the trap values the higher the corresponding glow peak temperature.

### 3.2.2- Historical survey

The major efforts to apply the (TL) phenomenon to geological and other related problems began in the early 1950's with Daniels et al. (1953). In the early period the most successful application of (TL) was in dosimetry. Daniels also made some early attempts to use (TL) as an absolute dating

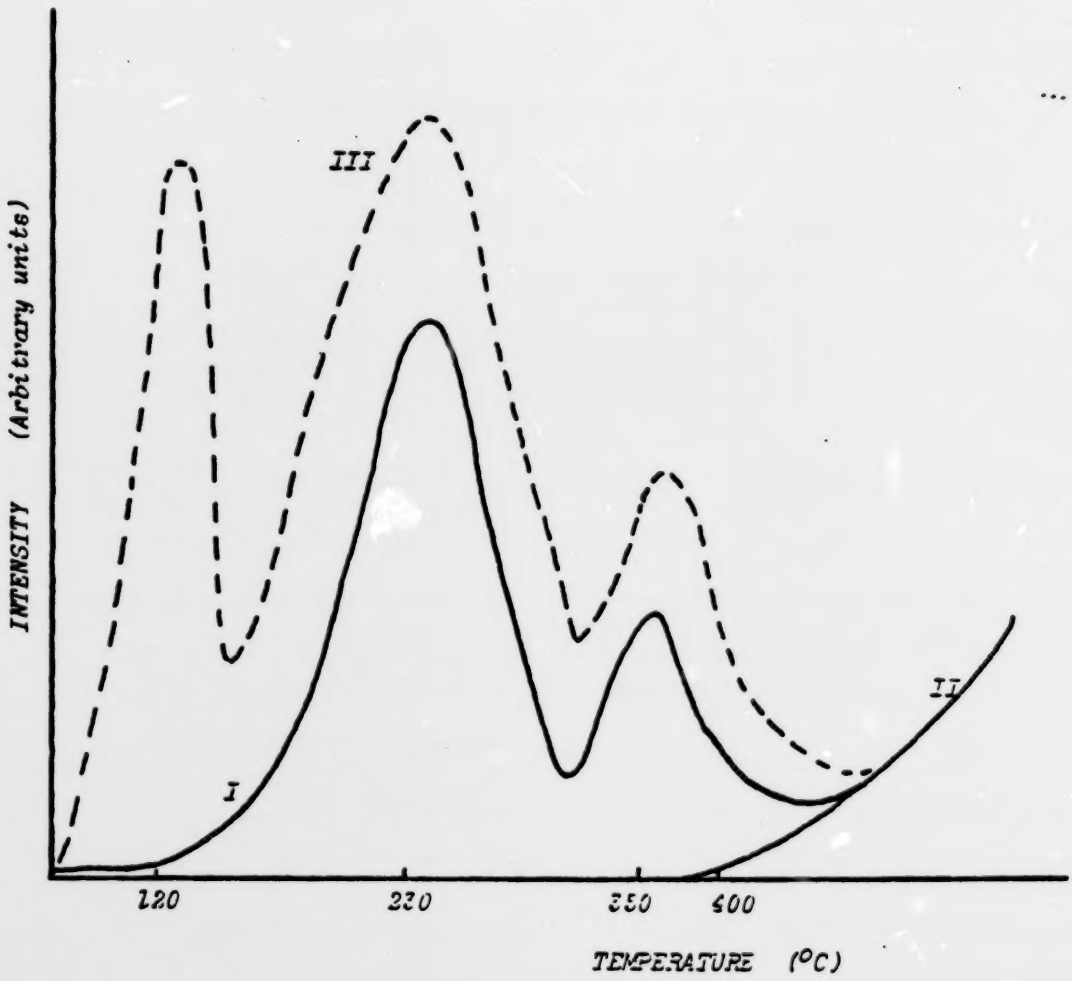



*Figure 1 Hypothetical thermoluminescence glow curves*

*I- Natural thermoluminescence (NTL)*

*II- Incandescence curve (Black body)*

*III- Artificial thermoluminescence*

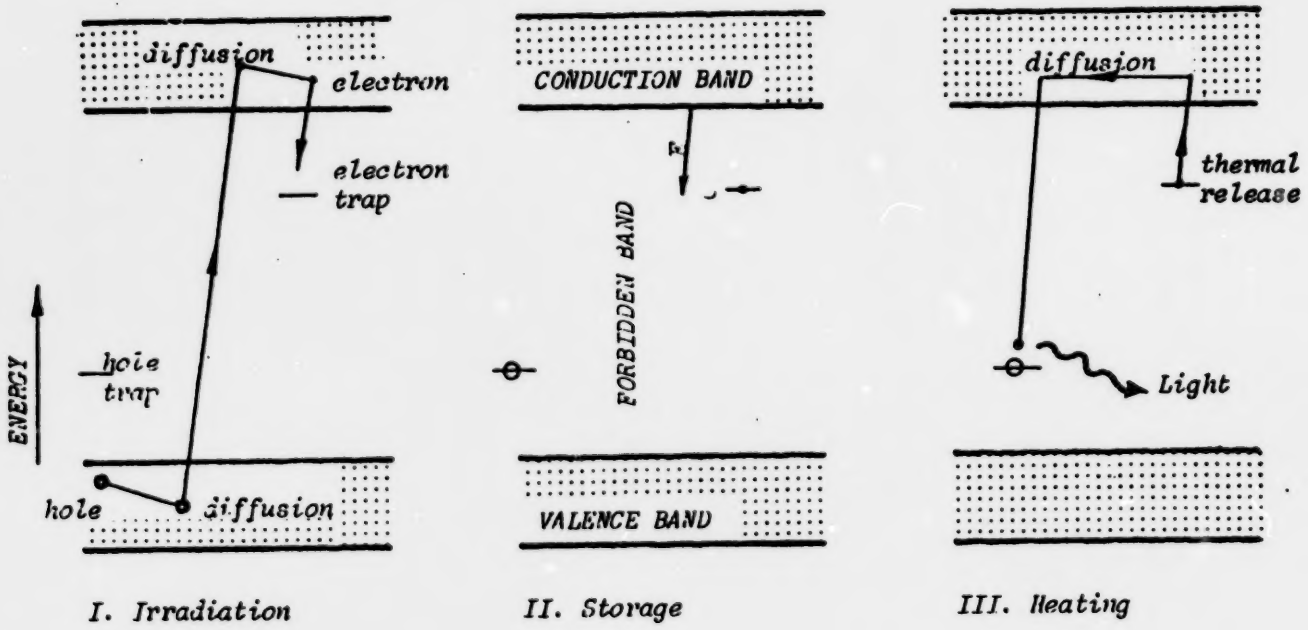



*Figure 2* *Band model illustrating an hypothetical electron displacement in a crystal lattice*

*(From Aitken 1974)*

technique, but with questionable results. Zeller (1968) summarized the attempts and the difficulties associated with the use of (TL) either natural or artificial in dating calcite and other geological materials. He concluded that most minerals including calcite are not good dosimeters. Therefore the light output is not easily correlated to the total radiation dose received by the sample.

In the early work, the phenomenon of (TL) was ascribed to ionizing radiation. Later Angino (1959, 1960) distinguished three types of (TL) which are classified according to the process that should cause the electron displacements:

- radiation induced
- pressure induced
- crystallisation induced

Later d'Albissin (1968), Morency (1968, 1973), McDougall (1970), Hess (1971) demonstrated the effects of pressure on the (TL) phenomenon. Pressure will bring about changes in the peak heights and also in the shape of the peaks.

The fact that (TL) is dependent on temperature, radiation and pressure renders the phenomenon versatile for possible applications to geological problems. On the other hand its application is made complex because of the need to separate and quantify each of the variables. This partly explains the early difficulties in using (TL) in age determination.

In the last decade (TL) has been most successfully used in archeometry for dating pottery (Aitken 1972). This success is related to two factors; first potteries were fired which, automatically sets the clock to zero by emptying the electron traps. Secondly the pottery materials are cryptocrystalline in nature. This small grain size flavors a uniform distribution of the radioactive elements and a uniform radiation effect. Ralph (1969) reported ages for pottery of $\simeq 10^3$ to $10^5$ years ± 25%. Although the error was large, the reported dates, were considered quite acceptable at the time. The large error was due to the assumption that only the alpha particles were responsible for the ionization effects. Following this, the microdosimetry technique was developed for archeometry, distinguishing and evaluating the individual effects of alpha, beta, gamma and cosmic radiations (further details are given under the section "microdosimetry").

Fleming (1966, 1970) developed the so called "quartz inclusion dating technique". It consist of separating quartz grains (40 - 70 μm) from the pottery and etching them with HF destroying the original surface of the grains and in the process eliminating the alpha dose contribution. Simultaneously Zimmerman (1967-1971) developed the "fine grain technique" The technique consits of using grains of (4 - 11 μm) sedimented on a disk. This procedure yields a homogeneous sample which is uniformly affected by all types of radiation. Both

techniques are applicable to pottery dating. The fine grain technique is presently the most extensively used and preferred in archeometry. It is now routine work to date artifacts within the range of $10^3$ to $10^5$ years with thermoluminescence (Aitken 1978, 1980).

More recently TL has been used successfully for dating quartz in Quaternary deposit (Lamothe 1982). The Russians have pioneered this work and claim that the technique could be used for materials as old as up to $5 \times 10^6$ years (HÜtt 1978).

Several other attempts are now underway to apply the techniques developed in archeometry to dating geological materials. However according to Valladas (1980) the application is not straight foward because the materials show significant differences in their impurities, content, distribution and grain size, and the ages involved are often much greater.

### 3.2.3- Theory

#### Basic principles

Natural radiation causes ionization in crystals, enabling electrons and holes to leave the valence band and become free to travel about the lattice. They are eventually trapped at various defects (i.e. impurities dislocation etc) in the crystal lattice (Figure 2, I). This trapping procedure is time dependent, thus a measurement of a number of filled traps theoretically can be used to determine an absolute age

(Figure 2, II). The necessary assumptions are that the natural radiation is constant and does not create additional defects, and that deformation (pressure) has not affected the trap distribution and electron trap population.

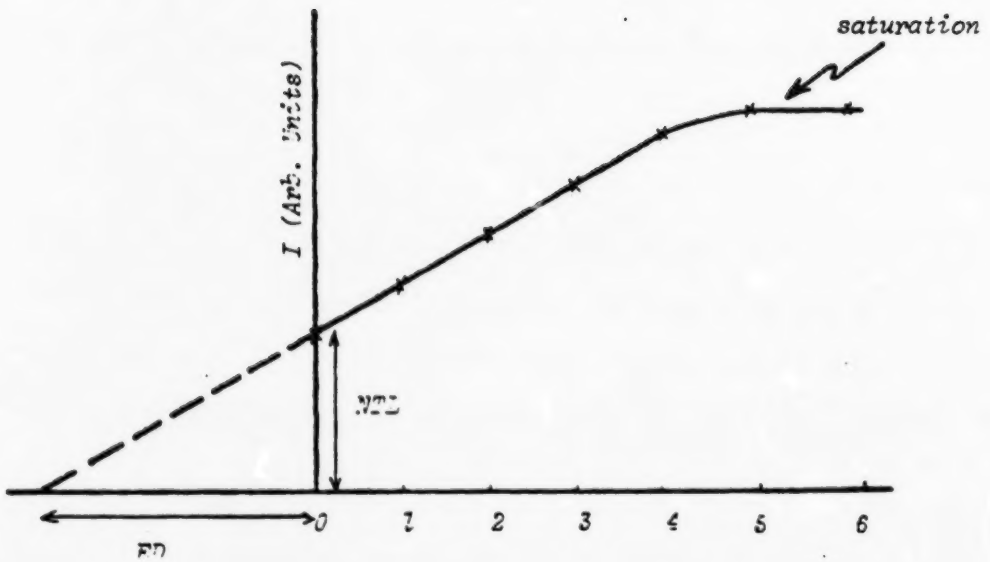
The NTL is a natural dosimeter reflecting the amount of radiation received by the sample. Its also represents a fixed portion of the trapped electrons which have recombined with holes at luminescence centers which are atoms or ions that will emit the energy received from the recombination in the visible part of the electromagnetic spectrum (Figure 2, I).

If the NTL responds linearly to additional artificial radiation doses, the equivalent dose (E.D.) or paleodose can be obtained (Figure 3).

Age (years) = E.D. (rads) / Dose rate (rads/year).
As illustrated in figure 3 the artificial thermoluminescence usually reaches saturation after doses of several kilorads.

Criteria for thermoluminescence dating

Wintle (1980) outlined a certain number of criteria that must be satisfied before a new material can be used for dating.




DOSE Kilorad

Artificial radiation

γ or β

*Figure 3 (TL) Equivalent dose determination diagram*

a) The mineral must have sufficient natural thermoluminescence response. This will vary greatly depending on its impurity content and transparency.

b) The mineral must have been set to zero in relation to its trap electron population. This criterion applies to all dating techniques whether physical or isotopic. In (TL) dating of pottery the firing of the material resets the electron trap population to zero.

c) The mineral should not exhibit "anomalous fading" of the peak used for dating. The NTL must be sufficiently stable with time i.e. the lifetime "t" of the trap population should be $10^9$ years (Table 2) in order to except an age determination in the range of $10^6$ years.

d) The NTL should respond in a linear fashion with artificial dose. The NTL signal should not be at saturation ortherwise the extrapolation for the determination of the paleodcse will not be accurate. If the sample is at saturation a minimum age can still be obtained, since the equivalent dose (E.D.) necessary to attain saturation can be evaluated.

e) The annual dose should be accurately determined. The microdosimetry of $\alpha$, $\beta$, $\gamma$ and cosmic ray must be precisely evaluated.

Kinetic calculation data on high temperature peaks of quartz show lifetime values for charge carriers in trapping centers, ranging from $10^7$ to $10^{10}$ years (Table 2). There is agreement, that if a high temperature peak having a high lifetime value is used, the technique of (TL) theoretically should yield dates of several millions of years. It was also found that high temperature peaks will not exhibit much fading.

As described before, the (TL) phenomenon is dynamic i.e. it can only be measured once and the light emission measurement is made at the end of a complex electronic displacement process. That process can include; normal charge transfer through the conduction band followed by recombination with luminescence and killer centers, re-trapping, tunnelling of various types, resonance energy transfer, etc...

Sample limitations

The criteria listed above for dating geological materials with (TL) are in fact the main sample limitations. The implication and the difficulties are associated with finding the proper material that will satisfy the criteria. Natural minerals have abundant and varied impurities, which render the electron and holes displacement complex and not always constant.

Table 2 Lifetime "t" for trapped electrons, quartz data from kineties calculations at 20°C

Aitken and Fleming 1972

| PEAK | LIFETIME "T" |
|---|---|
| 100°C | 3 hours |
| 200°C | 1 year |
| 300°C | 3,000 years |
| 400°C | $10^7$ years |
| 500°C | $3 \times 10^{10}$ years |

Fleming 1969

| PEAK | TRAP DEPTH | TIME | LIFETIME "T" |
|---|---|---|---|
| 110°C | .99 ev | $8 \times 10^{12}$ $s^1$ | 3.5 hours |
| 325°C | 1.26 ev | $4 \times 10^{10}$ $s^1$ | 3,000 years |
| 375°C | 1.66 ev | $1.5 \times 10^{13}$ $s^1$ | $4 \times 10^{10}$ years |

### 3.2.4- Problems associated with (TL)

#### Technique limitations

With the conventional (TL) apparatus the highest temperature peak that can be measured is around 500°. This limitation results from incandescence increasing in intensity at a temperature of approximately 400°C and masking higher temperature peaks. This appears to be the most serious limitation of the technique in attempting to extend its range to values of several tens of millions of years. Impurities, disorders, dislocations and other defects brings charge disequilibria that behave as charged trap particles.

Calcite usually has a high NTL response with as many as four peaks having been reported for Iceland Spar (Medlin 1964). The (TL) response is mainly related to the presence of $Mn^{+2}$ which occupies substitutional sites in the lattice. Additional impurities such as ($Mn^{+2}$ (in excess 100 ppm) Ti, Cr, $Fe^{+2}$ etc) complicate the electronic process. Medlin (1964), (1968) reported on the mechanism responsible for the (TL) of calcite and concluded that there is still a lack of information about the trapping centers, and the mechanism for exciting emissions when the traps are emptied. Wintle (1978) showed that calcite from a speleothem had (TL) characteristics, which, based on kinetic grounds, should be stable to values that would permit absolute age dating up to $\simeq$ 1 million years. Even though calcite exhibits a high (TL) signal it is usually inhomogeneous in its

luminescence centers and radioactive elements distribution. It also exhibits spurious (TL) which is related to various complex surface effects. These factors limit the dating possibility of calcite by (TL) alone.

Quartz does not have a high NTL response and it usually exhibits two peaks at 325°C and 375°C. Because of its abundance and dosimetry properties (Mc Dougall 1971), quartz is still being extensively studied for age dating.

Natural quartz is not free of impurities but its structure restricts or discriminates to a greater extent against the inclusion of foreign ions (Sutton 1978). McMorris (1971) suggested that quartz has aluminium impurities acting as hole traps whereas Li, Na, and Ge are charge compensators in interstitial positions. Oxygen vacancies and charge compensators behave as electron traps.

Materials with a high saturation dose level and a low radioactivity environment are the most promising to use in attempting to extend the maximum age to several millions years. The low radioactivity prevents the saturation of the electronic traps and theoretically would allow the determination of the paleodose for older samples.

### 3.2.5- Microdosimetry

Potassium-40 and Rubidium-87 disintegrate by the emission of beta particles. Uranium-238, Thorium-232 disintegrate by emitting alpha, beta and gamma. The latter elements are the

only ones to be considered in the evaluation of the alpha (TL) production.

The microdosimetry that was developed in archaeometry evaluates independently the effects of each type of radiation. Considering the grain size, an annual dose contribution per p.p.m. of radioactive parent present in the sample is compiled, considering the efficiency of the radiation and the grain size of the sample. The concentration of radioactive elements can be obtained by several methods, including, chemical determination, neutron activation or by phosphor dosimeters.

The efficiencies for ionization and the penetration range are different for each type of radiation. Alpha radiation is more efficient in creating ionization than beta particles The corresponding ionization rate per unit length is 1,000 times larger for alpha than beta but its range is 1,000 times less. In addition the alpha ionization density increases gradually to a maximum where it comes to rest. As a consequence the proximity of electron - hole production associated with the ionization process make recombination likely . (Levy 1974). The combined effects of the above make the $\alpha$ particles about 10 times less efficient in the (TL) production when considering equivalent doses. In addition alpha are related to the presence of uranium and thorium in minerals, these elements are usually concentrated at the boundaries or between grains.

In a solid with a density of 2.7, a 5 Mev alpha particle will only affect the outer 25 μm layer. In the quartz inclusion dating technique if hydrofluoric acid (HF) is used to reduce the grain size diameter this will render the effect of alpha particles negligeable. For other minerals and other techniques an alpha dose rate estimation would have to be determined.

The beta radiation has a range in the order of a few millimeters. A 5 Mev electron will travel 5 mm before it comes to rest. The gamma radiation is highly penetrative; a 1 Mev γ can penetrate up to 15 cm. Therefore the ionization process will be effective throughout the crystal lattice. Bell (1979) gave the most recent dose-rate estimations (in rad/yr) for 1 ppm by weight of parent (Table 3). To evaluate the annual dose received by the mineral, a separate evaluation of the internal dose (di), (α, β) and the external dose. (de) (γ, cosmic rays) is made

d = di - de

α = can be neglected in certain minerals

The background radiation (γ and cosmic rays) can be evaluated by placing dosimeters on the sample collecting sites or by other techniques. The cosmic rays dose will depend on the depth at which the sample was collected and its latitude.

It is critical to evaluate the annual dose accurately, otherwise large errors will be incorporated in the resulting dates.

Table 3 Dose-rate (mrad/yr) for 1 ppm by weight of parent

| | α | β | γ |
|---|---|---|---|
| Thorium series | | | |
| (no Thoron loss) | 73.8 | 2.86 | 5.14 |
| (100% Thoron loss) | 30.9 | 1.03 | 2.08 |
| Uranium series | | | |
| (no Radon loss) | 278.3 | 14.62 | 11.48 |
| (100% Radon loss) | 126.2 | 6.09 | 0.56 |
| Natural Potassium | | | |
| 1% $K_2O$ | ____ | 68.93 | 20.69 |
| Natural Rubidium | | | |
| 100 ppm Rubidium | ____ | 4.64 | ____ |

(From Bell 1979)

### 3.2.6- Published age results by (TL)

Table 4 list the published (TL) age results of different materials including results for the minerals under consideration.

### 3.2.7- New advances

As already stated, depending on the apparatus, the (TL) measurements are normally made by heating the sample up to about 500°C. Valladas (1979), using a thick UV filter was able to observe the (TL) signal from volcanic plagioclases at temperatures up to 700°C. They also concluded that (TL) signal above 600°C is not subjected to either anomalous or thermal fading. Those higher temperature peaks show promise for dating older geological materials.

Another approach in measuring electrons from deeper traps is by phototransferred measurements which were applied successfully on feldspars (Bailiff 1976, Bowman 1978). Phototransferred (TL) measurements involve bleaching deeper traps by optical means (Bowman 1978). The electrons liberated in this fachion are retrapped at sites corresponding to measurable glow peaks of lower temperatures. Although the experiments were made with young material ($10.2 \times 10^3 \pm 1.4$ years) the results are in good agreement with radiocarbon dating ($7.65 \times 10^3 \pm 0.35$ years). It appears that the technique is accurate and offers potential for older samples.

Table 4 Published (TL) age results

| Material | Age | Reference |
|---|---|---|
| Potteries and artifacts | $10^3$ to $10^5$ years | Aitken and Fleming 1972<br>Zimmerman 1971 |
| Quartz in sedimentary deposits | $2.5 \times 10^4$ to<br>$9.2 \times 10^5$ years | Skelpophyas (1974)<br>Hütt and Raukas 1977 |
| Calcite from speleothem | $10^6$ years | Wintle 1978 |
| Plagioclase from lavas | $3 \times 10^5$ years | Valladas 1980 |
| Deep sea sediments | $1.4 \times 10^5$ years | Wintle and Huntley 1979 |

Although still at an early stage, image intensification techniques already seem to provide a powerful tool for the study of (TL) inhomogeneous materials like calcite (Walton et al. 1980). This technique allows, microscopically, the selection of regions at the surface of the sample for age dating. This selection will compensate for anomalous high (TL) related to heterogeneous distribution of (TL) activators and inhibitors. This technique would be used in conjunction with a micro-thermoluminescence apparatus.

### 3.2.8- Summary

It can be concluded that both calcite and quartz can now be dated up to ages of $1 \times 10^6$ years. Russian dates for quartz have been reported with values up to $5 \times 10^6$ years. Presently, of the two minerals, quartz being a better dosimeter appears to be the best candidate to yield older ages.

With improvements of the (TL) apparatus (i.e. UV filter photon counting ETC.) is probable that still older ages could be obtained. It is likely that the present tendency of combining (TL) and image intensification for example in studying artificial crystals will be extended in a few years to natural material. This hopefully will reduce the age error and push back the time barrier to values up to $10 \times 10^6$. It appears presently doubtful considering the complexity of the phenomenon, that this value would be extended by a factor of 2 or 3 using (TL) alone.

## 3.3- Electron Spin Resonance

### 3.3.1- Introduction

Electron spin resonance is a technique of determining with microwaves, the presence of electrons trapped in the structure of some crystalline materials. Unpaired trapped electrons can absorb energy from a microwave beam ; the absorbance value is a measure of the electronic population. Contrary to (TL), this measurement can be made repeatedly without

affecting the trap population. Prior to being trapped, the electrons are released from their parent atoms by radiation from radioisotopes present in the minerals and the host rock.

The principle of ESR dating is essentially the same as (TL) dating. (TL) is observerd when the trapped electrons recombine at luminescence centers while ESR is a method which evaluates the electronic trap population.

3.3.2- Historical survey

Zeller (1967, 1968), Morency (1969), attempted to apply the ESR dating technique to minerals. They have established that several minerals have an ESR signal that could be used for age dating. Ikeya (1975, 1978), has reported dates of $3.3 \times 10^5$ years for calcite from stalactites and stalagmites. More recently Garrison (1981) obtained dates on ancient flints in the range of $300 \times 10^6$ years ± 30%. Although the error is presently large, it is possible that improvement in sample selection and preparation could reduce the error, for instance, an oriented single crystal could be used, yielding sharper resonance peaks.

3.3.3- Theory

In contrast to (TL), ESR is a static process, the measurement of the trapped electrons can be made repeatedly without affecting the population.

Electron spin resonance refers to the magnetic resonance of a permanent dipole moment. A rough macroscopic analogy might be that of a spinning top processing about the direction of a gravitational field. Pictorially, an electron with moment $\mu$, when placed in a constant magnetic field $H_0$ processes about the direction of $H_0$ at a constant angle $\theta$ with a natural frequency given by:

$W = \gamma H_0$ (Larmor precession), where $\gamma$ is a constant.

If we apply microwave radiation, which is a small rotating magnetic field 'h' in a direction perpendicular to $H_0$ and having the same frequency as that of the precessing electron, $\theta$ will increase as the system absorbs power from the incident microwaves. Under these conditions the system is said to be "on resonance". Experimentally, the frequency of the incident microwaves if fixed and $H_0$ is varied such that as the system goes through resonance the power absorbed by the sample is recorded by observing the variation of the power level of the microwaves. Since materials such as phosphates carbonates and quartz have a paramagnetic system (one in which the electrons do not interact), any measure of the power absorbed (e.g., peak height, width at half-power points) will be a relative measure of the number of trapped electrons in the sample (Figure 4) (Morency 1969).

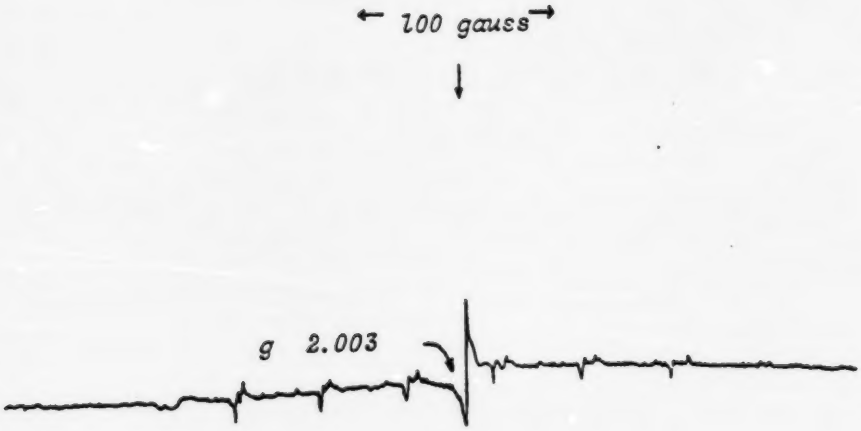



*Figure 4 ESR derivative lines of a stalactite from Akiyoshi cave. The signal at central position indicated ( g 2.003) is associated with the defect destroyed at 330 C. This signal intensity can be used to estimate the total dose of the natural radiation (Archaeological dose). The modulation width is about 4 gauss. (From Ikeya 1978).*

Background radiation from uranium, thorium, potassium, rubidium and cosmic rays produces ionization or free electrons which literally wander through the crystalline structure and are eventually trapped in defects called electron traps. Traps are various types of crystalline imperfections introduced during the crystallization process. Background radiation can also cause defects, but according to Zeller et al. (1967) the formation of additional defects will be negligible if the background level is low.

The principle of ESR dating is essentially the same as (TL) dating. It consists of first determining the ESR signal induced by the natural background radiation and then subjecting the sample to small additional doses of artificial radiation to establish the dependence of signal growth on radiation dose, (Figure 5). If the signal growth is linear, by assuming a constant natural dose rate, a linear extrapolation can be made to determine the total natural radiation dose received by the sample. Applying the microdosimetry techniques described in section (3.2.5) the annual dose or dose rate can thus be determined and an age calculated.

Age (years) = E. D. (rads) / Dose rate (rads/year)

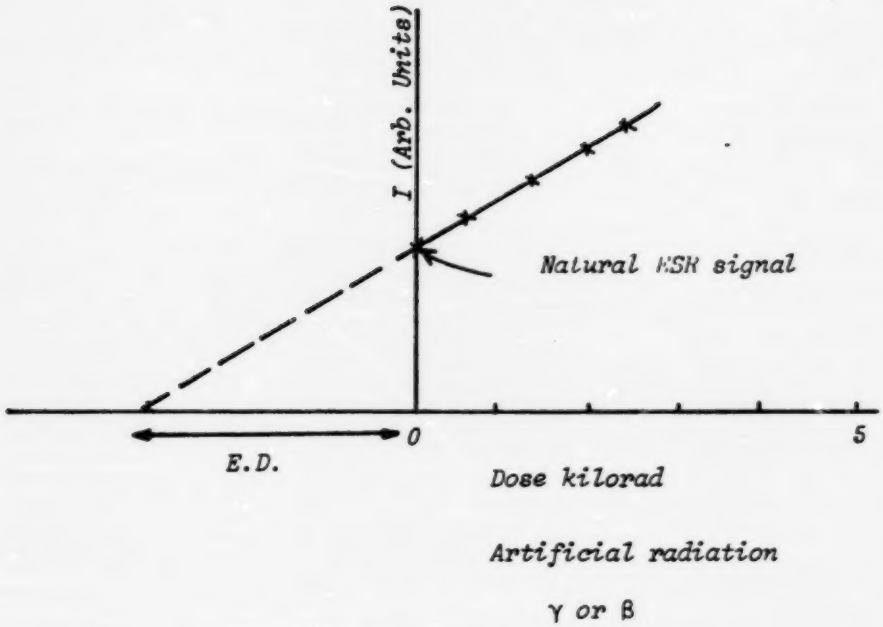



*Figure 5 ESR Equivalent dose determination diagram*

### 3.3.4- Advantages of ESR

Being a static measurement process, the radiation induced effect is not destroyed during the measurement as in the case of (TL) or TSC.

The signal is representative of the electron population in the trap and, unlike (TL) or TSC, ESR will not be affected by such phenomena as tunneling, resonance energy transfer and other similar effects.

In ESR - both a single crystal or polycrystalline material can be used. With polycrystalline samples no special grinding or preparation is needed, only small amounts of sample are needed ($\simeq$20 mg). Chemiluminescence, spurious luminescence, lack of transparency and black body radiation are variables which will not interfers in the measurements. A single crystal offers even more possibilities since it can be preferentially aligned with respect to the field strength $H_0$ and could yield additional results on the nature of the defects, its trapping capacities and its lifetime values.

### 3.3.5- Disadvantages of ESR

According to Ikeya (1978) a minimum of defects in excess of $10^9$ spins is needed in order to yield a signal that can be used in age determination. Thus, ages younger than of 500 - 1000 years cannot be measured.

The presence of large amounts of $Fe^{+3}$ $Mn^{+2}$ and rare earth ions in calcite give ESR signals due to unpaired electrons. The presence of these impurities could yield peaks which will overlap with peaks from trapped electrons and prevent their measurements.

3.3.6- Published age results

Eventhough ESR work on geological materials have been going on sporadically since the middle sixties, few dates have been published for the minerals under considerations. Table 5 list the most recent results on quartz and calcite.

Garrison has demonstrated that quartz can be dated for several tens of million of years. Ikeya as showed that calcite should yield dates of approximately $10^6$ years since annealing studies at 27°C as yielded lifetime trap values "t" of $10^9$ years and should not show anomalous fading or fluctuation in the electronic population.

3.3.7- Summary

Being a static process and also capable of measuring deep traps without the interference of incandescence, transparency, and surface effects, ESR could apply to several minerals including quartz and calcite.

Of the radioactive dating techniques considered ESR is the only one that has successfully dated

Table 5 Published (ESR) age results

| Material | Accepted Geological Age (10 years) | ESR Age 30% |
|---|---|---|
| Flint - Oklahoma | 370 | $310 \times 10^6$ years |
| Flint - Utah | 250 | $366 \times 10^6$ years |
| Flint - Africa | 3200 | $57 \times 10^6$ years |
| Flint - Missouri | 320 | $333 \times 10^6$ years |
| Flint -Illinois | 320 | $280 \times 10^6$ years |

(From Garrison 1981)

| | |
|---|---|
| Calcite | $1 \times 10^5$ years |

(From Ikeya 1978)

the minerals under consideration up to several hundreds of millions of years. Therefore technique has a definite potential for dating secondary quartz and calcite found in faults and should seriously be considered.

## 3.4- Thermally Stimulated Current (T.S.C.)

### 3.4.1- Introduction

Thermally stimulated current measures the electron population in the conduction band (Figure 2). At this level of energy the electrons are literally free to travel through the crystal lattice producing a transient current.

### 3.4.2- Theory

Trapped electrons which are thermally released into the conduction band through a charge transfer process create a transient current. This current is proportional to the portion of the trap electron population which involves a charge transfer to the conduction band, resonance energy transfer and tunneling will not contribute to the measurement. As in the case of (TL) and ESR the trap electron population was created with time by natural ionizing radiation.

The principle of the thermally stimulated current dating technique is similar to the basic principle of thermoluminescence and electron spin resonance techniques.

The TSC curves are similar in appearance to (TL) glow curves (Figure 6), showing peak current at different temperatures. The TSC peak also varies linearly with artificial radiation. In contrast to (TL) where saturation is often reached after several kilorads, TSC appears linear even after artificial doses in the megarads range (Hwang and Fremlin 1970). The age equation used in the discussion for (TL) and (ESR) techniques is applicable to the TSC method (Figure 7).

Age (years) = E. D. (rads) / Dose rate (rads/year)

3.4.3- Advantages and disadvantages of T.S.C.

Advantages

TSC is either not responsive or is less responsive than (TL), to some of the following features.

- saturation in the megarads range.
- non uniform distribution of luminescence centers and impurities since a larger area is considered.
- lack of transparency of sample.
- incandescence or black body radiation.
- spurious, chemiluminescence or other surface effects.

Disadvantages

- experiments are performed on solid samples, therefore greater care is required in selecting and preparing the samples.

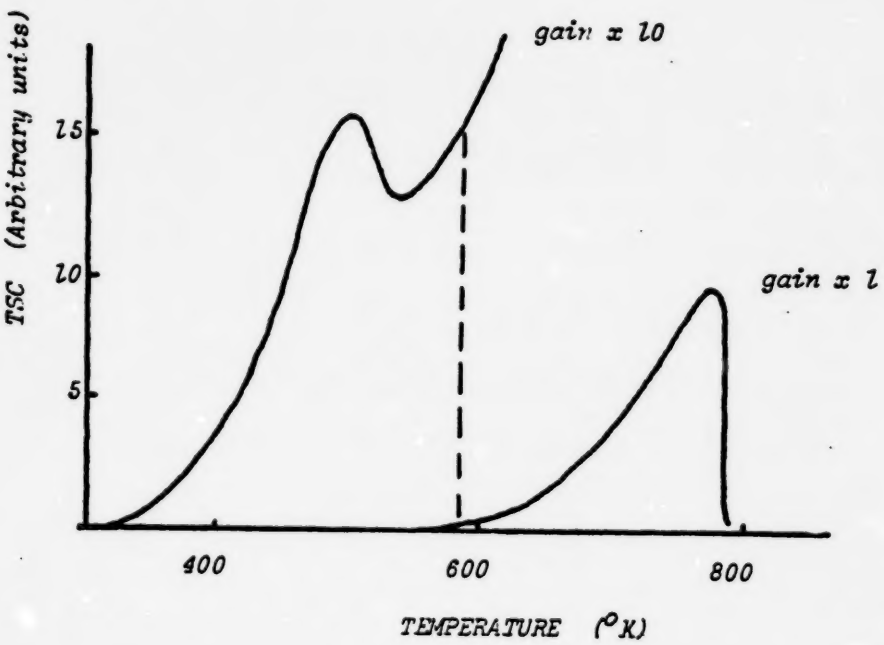



*Figure 6 Thermally stimulated current curves (After Katzin et al 1975)*

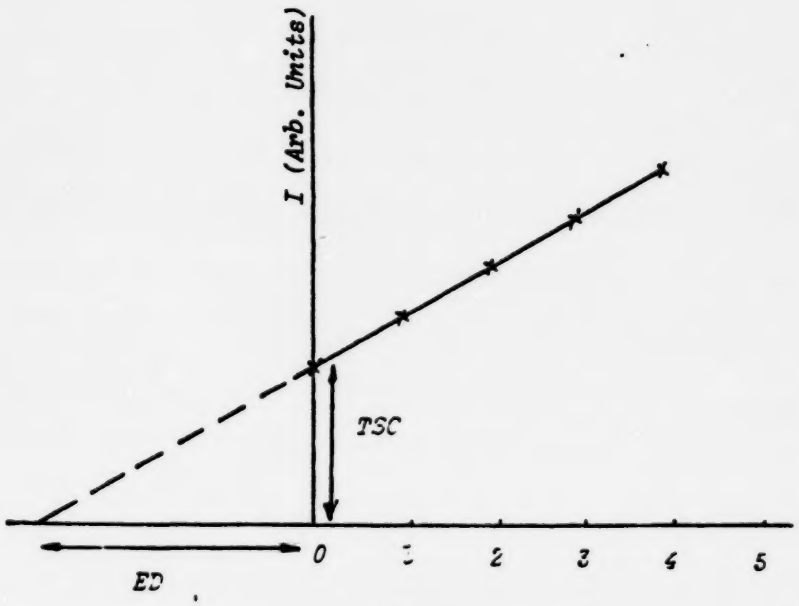



*Figure 7 TSC Equivalent dose determination diagram*

- reproductibility and accuracy of the transient current determinations is poor.

### 3.4.4- Published age results

Hwang and Fremlin (1970) are the only one that thave reported age determination of geological materials by TSC (Table 6). The rocks dated were basalts which were also dated by K/Ar. Two of the three dates show good agreement with K dates. The discrapency on the third date was vaguely related to argon loss. No major reasons or explanation were found to explain the lack of interest for the TSC age dating technique. However recent studies mentions correlation work between (TL) and TSC signal on artificial crystals.

### 3.4.5- Summary

Hwang and Fremlin (1970) stated that because TSC does not saturate at low radiation doses, the method therefore seems to be applicable to ages in the range of 1 to 3 x $10^6$ years. When compared to (TL), TSC theoretically shows greater potential for dating older samples, but no TSC curves of natural mineral have been produced in recent studies that would confirm this assumption. Experimentally it should be straight forward to establish if a TSC peak exists at very high temperature. Valladas (1980) reported some (TL) peak at 700°C so that it seems resonable to expect an equivalent TSC peak. Without the effect of incandescence and other surface effects TSC should be be able to look into deeper electrons traps and therefore yield much older ages.

Table 6 Published (TSC) age results

| Material | $^{40}K$ age (x $10^6$ years) | TSC (x $10^6$ years) |
|---|---|---|
| basalt - McMurdo Antarctica | 2.0 | 2.17 ± 0.47 |
| basalt - Montsenalt | 1.52 ± 0.26 | 1.42 ± 0.52 |
| basalt - St-Vincent | 4.8 ± 1.5 | 16.32 ± 428 |

(From Hwang and Fremlin 1970)

## 3.5- Combined, TL, TSC, ESR Techniques

### 3.5.1- Introduction

From what has been stated in the previous sections it is obvious that (TL), TSC and ESR are related to the electronic trapped population and their subsequent movements. Essentially all these techniques provide a mean of measuring electrons directly trapped or en route to recombination centers.

### 3.5.2- Historical survey

Since the early parts of the seventies; there has been a growing interest in comparing signal response from the various radioactive damage techniques applied to artificial crystals doped with particular foreign ions.

Katzir (1972) Casiot (1977) reported on correlation studies between TSC and (TL) in boron nitride crystals. Katzir (1975) studied the same crystals by ESR, (TL) and TSC. Bryant (1974) also studied zinc sulphide by TSC and (TL).
They all point to a close correspondance among (TL) glow peak, TSC transient current and ESR trapped electronic population.

3.5.3- Theory

In naturraly occuring rocks and minerals the mechanism involved in electronic charge transfer are usually more complex then in artificial crystals. The combined technique (TL, TSC and ESR taken together) will enable us to monitor all possible energy transfers which are involved. Once trapped in the forbidden band (Figure 2) the electron can follow several routes back to a normal energy position:

1°- Electronic processes involving the conduction band

a) normal charge transfers to conduction band and recombination at luminescence or killer centers in which case there is light or no light emitted respectively.

b) normal charge transfers to conduction band followed by re-trapping into deeper traps.

2°- Electronic processes not involving the conduction band

a) the electron passes directly to luminescence or killer centers by tunneling.

b) other processes, including resonance energy transfer.

If a combination of the three techniques are used, the following measurements and information could be obtained. Corrections factors could then be applied and an older, more accurate age determined.

- the trapped electrons measurements before thermal release could be made with ESR. Accordingly the trapped electron population would be characterized.

- once the electrons are released, TSC would modulate the electron traffic in the conduction band. In this fashion tunneling and resonance transfer could be accounted for.

- finally (TL) would yield the amount of recombination at luminescence centers.

This approach should add considerable information needed for dating purpose. If TSC and (TL) have close correlation indicating a charge transfer through the conduction band than the sample is a good dosimeter if no killer centers are present in large quantities. The combination of the three physical techniques could also be valuable in monitering the phototransfer of electrons (see section 3.2.7) from deeper electronic traps.

Figures 8a and 8b illustrate the correlation existing between the three techniques. In this particular example, the good agreement between TSC and (TL), although qualtitative in nature, indicates a charge transfer through the conduction band. This is followed by recombination at luminescence centers and no or little retrapping, tunneling or resonance transfer is involved. Figure 8b illustrate the fashion in which the trapped population for two sets of trap depth, are annealled with temperature.

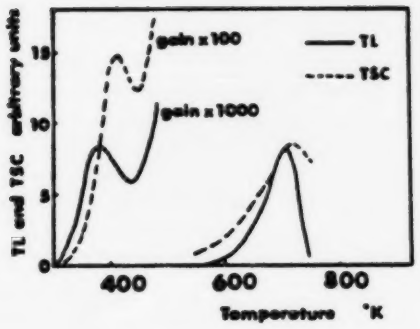



*Fig. 8a* *Thermoluminescence (TL) and thermally stimulated current (TSC) curves for BN. After Katzir, Suss and Halperin 1972.*

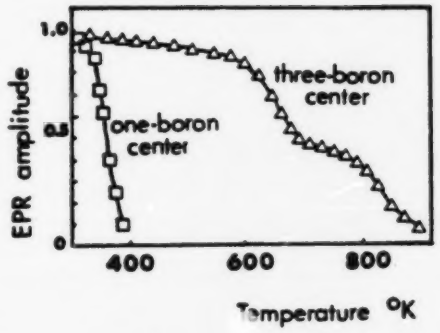



*Fig. 8b* *Isochronal annealing of EPR spectra of the one-boron and three-boron centers in BN. After Katzir, Suss and Halperin 1972.*

### 3.5.4- Summary

(TL), TSC, and ESR are presently used to study artificial crystals. The inter cuve correlation between the above techniques is excellent. It is anticipated that in the near future, the three techniques combined will be applied to natural minerals for the purpose of age dating. This will help understand the mechanisms involved in the complex electronic transition from the valence band to the recombination center. Studies undertaken during the next decade should evolve in this direction and yield solutions to the old problems that have always plagued the (TL) dating technique.

## 4- PRESSURE (Stress and Strain) INDICATORS

In this section (TL) and/or triboluminescence are considered as a possible monitor of changes in the stress-strain conditions of a rock mass. (TL) and triboluminescence are sensitive to dislocations, micro-fracturing, failure and grinding. Changes in the (TL) light signal have been associated with the formation, propagation and annihilation of dislocations which can behave as electron and hole traps (Mc Dougall 1971). Therefore the technique could be used as a pressure indicator before micro-fracturing develops or before deformation becomes apparent or detectable by strain gauges.

### 4.1- Thermoluminescence as Strain Indicator

#### 4.1.1- Introduction

The following discussion deals with the rock mass bounding a fault along which movement as occured and does not apply to the secondary minerals calcite or quartz that could be found with in the shear zone.

In order to evaluate the stress-strain condition in the rock mass, traverses of several hundreds of meters perpendicular to the fault would be made and samples would be collected at regular intervals. Mineral separates would then be analysed for signal changes in (TL). These signal changes would be compared with the (TL) signal characteristics of the body at a distance considerably removed from the fault (in order to get a "background value". In order to do this we

must assume homogeneity in the distribution of the minerals and the radioactive elements.

### 4.1.2- Historical survey

The initial effect of increasing strain is usually manifested by a change in amplitude of one or more glow curve peaks and an increase in the total light emission. In some cases, strain may cause either the appearance or disappearance of certain glow peaks (Morency 1968). Studies made in the vicinity of shear zones, show that the (TL) signal is usually less in and adjacent to the fault, than it is in the unfaulted rock (Morency 1973). The signal modifications are compared to the normal (TL) signal away from the faults is (i.e. (TL) background signal of the body).

The causes of change in (TL) due to strain is not well understood, in part at least, appears to be related to the formation annihilation and propagation of lattice dislocation which can act as electron and hole traps.

### 4.1.3- Hypothesis

The fundamental hypothesis used in such a study is the assumption that the natural and artificial thermoluminescence of a rock formation is be reasonably uniform in an area where:

1- the mineralogical composition and trace element content are constant

2- the background radioactivity is uniform

3- any subsequent metamorphism is either low grade or completely lacking

Under these conditions, if changes in thermoluminescence are observed in the vicinity of fault, then the changes can probably be attributed to deformation and failure of the rocks in and adjacent to the fault.

A hypothetical example of this relationship is expressed graphically in figure 9 whereon:

a) A & $A^1$ are the normal signal levels of thermoluminescence where strain effects are at minimum i.e. background level for the rock mass.

b) C & $C^1$ are the maximum deformational effects and (TL) response without failure.

c) D represents the level within the shear zone.

If recent movement occurred along the fault the signal level of D should be equal to or lower than the signal found at A or $A^1$. This is because the recent movement has destroyed the (TL) signal and the background radioactivity has not had sufficient time to rebuild the signal.

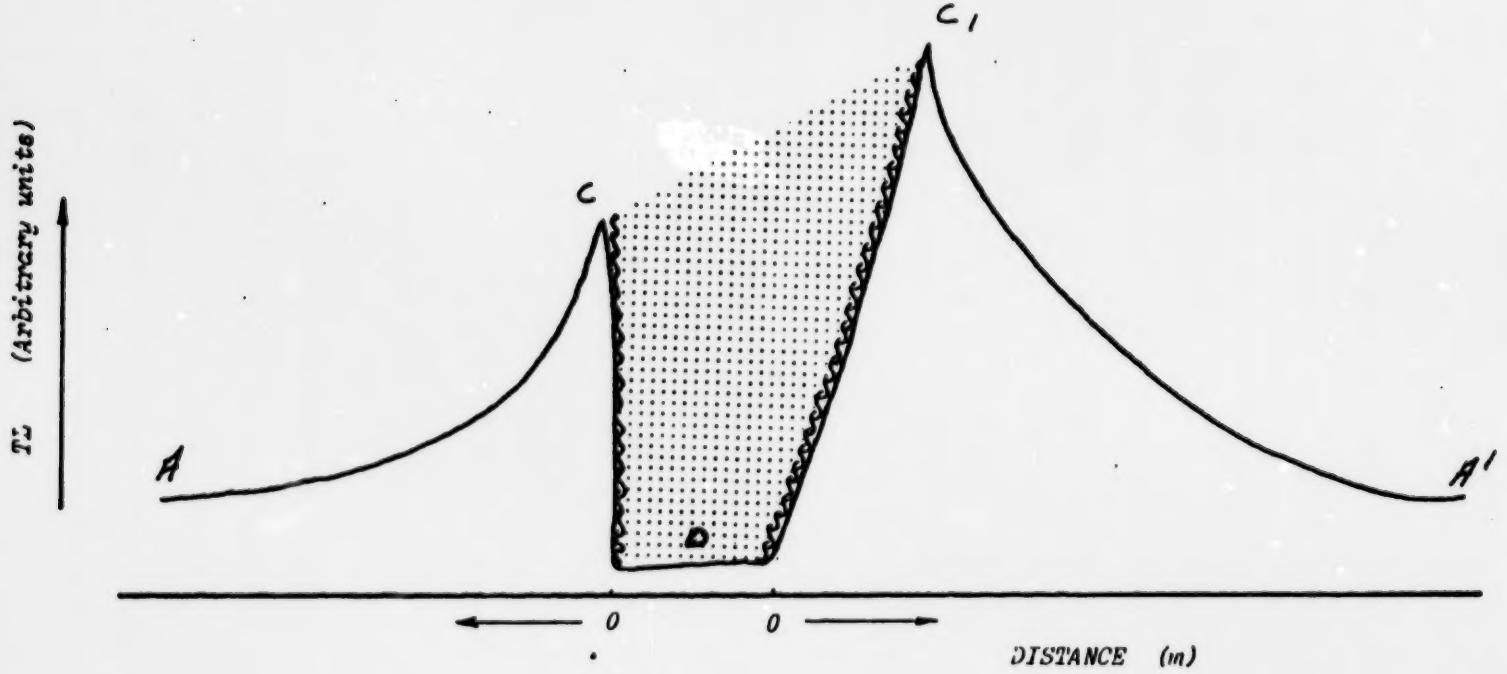



*Figure 9* *(Hypothetical case) Thermoluminescence variations from minerals and rocks close to and in fault zone. (After Morency 1973)*

Another possible situation is depicted in figure 10 where A, $A^1$, C and $C^1$ are as above.

The signal level D in the fault is higher in this case than the background value A & $A^1$. This high signal in the fault could be explained by the fact that the most recent movement occured a relatively long time ago and consequently the radioactive elements, combined with strain remnants, have had sufficient time to rebuild the signal level.

Furthermore, assuming that during the last movement the signal "D" in the fault had been completely destroyed, a minimum age determination for this last movement is possible. The value of "D" measured now is equivalent to the natural (TL) and it becomes the natural dosimeter since the last event (the last movement has set the clock to zero). The basic principles in age dating discussed for (TL), TSC and ESR can be applied to determine this minimum age.

For such an evaluation, the strain effects on (TL) would have be evaluated at different pressures leading to failure. This evaluation could be made with a triaxial chamber. Trace element distributions would have to be established, since some are possible activators or suppressors of (TL). A microdosimetry study should be conducted to assert the background in the rock mass and around the fault.

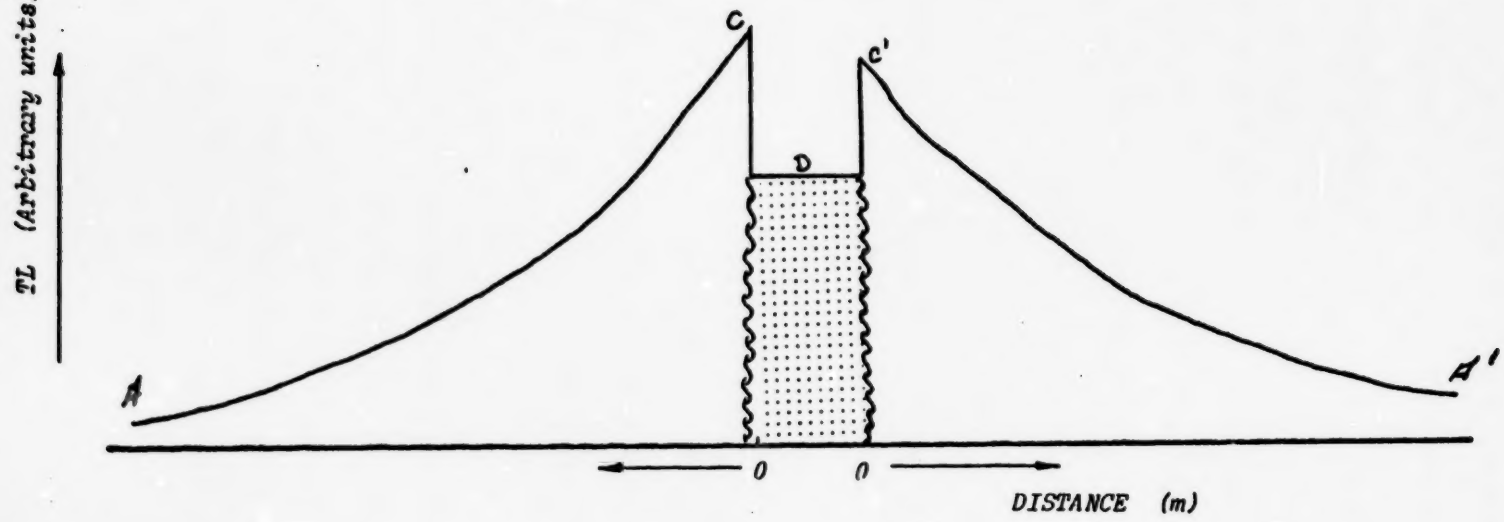



*Figure 10 (Hypothetical case) Thermoluminescence variations from minerals and rocks close to and in fault zone. (After Morency 1973)*

## 4.2- Triboluminescence

### 4.2.1- Introduction

Triboluminescence can be defined as light emission from many naturally occurring minerals as a result of either grinding, micro-fracturing, or failure. The phenomenon has been known since at least the sixteenth century. Depending on the minerals the phenomenon continues in either air or water for hours and days after mechanical excitation had ended; however, the photon flux decreases with time.

Usually the first burst of light can be observed by the unaided eye in a dark room and the later process can be easily detected with a photomultiplier tube. Contrary to thermoluminescence this phenomenon can be triggered without heating the sample. The decay of triboluminescence is variable, lasting from minutes to days, depending on the minerals.

### 4.2.2- Summary

Lahav (1981) examined prolonged triboluminescence in many solids: glass, quartz, calcite, marble, talc, pyrophyllite, ilmenite, apatite, asbestos, etc. All showed prolonged triboluminescence with quartz exhibiting the strongest triboluminescence effects and the smallest decay rate.

The same authors recommended that "the prolonged triboluminescence" should be investigated in connection with processes in which it is either naturally of artificially induced. Examples of natural process include rock fracturing, expansion-contraction, the impact of meteorites, and fault formation. Prolonged artificially induced thermoluminescence is very common in mines and quarries.

## 5- CONCLUSIONS

It is evident that the physical techniques, thermoluminescence (TL), electron spin resonance (ESR, EPR) and thermally stimulated current (TSC) are the only techniques that offer a potential for dating calcite and quartz. In addition each physical technique is capable of yielding a minimum age even if the samples have a signal that has reached a saturation level.

### Thermoluminescence

(TL) can date calcite as old as $1 \times 10^6$ years and quartz as old as $5 \times 10^6$ years. It is anticipated that with improvements to the (TL) apparatus (i.e. thick U.V. filter), the signal from deeper traps will be measured and older ages will be attained.

Improvements to the (TL) technique can be achieved with the addition of the phototransfer or image intensification techniques In this fashion, in the near future, it is expected that ages of $10 \times 10^6$ years could be obtained.

### Electron Spin Resonance

ESR offers advantages over (TL) for dating quartz, because it is capable of measuring signals from electrons in deep traps without the interference of incandescence. Transparency and surface phenomena have no limiting effects and the technique has been applied successfully to both calcite and quartz.

Garrison (1981) has demonstrated that ESR can date quartz samples as old as $3.66 \times 10^8$ years. Calcite ages of $1 \times 10^5$ years have been obtained.

Thermally Stimulated current

There are no recent TSC studies of natural minerals and rocks. On theoretical grounds the technique could be applied to both calcite and quartz. Not being affected by incandescence, transparency and many surface effects the technique should detect charge transfer to the conduction band at high temperatures yielding ages in the range of 1 to $3 \times 10^6$ years.

Combined TL, ESR, TSC techniques

It is likely that the present tendencies, in solid state physics, of combining (TL), ESR and TSC in an attempt to characterize electron displacement in artificial crystals will be extended, in a few years, to natural materials. This will have the effect of reducing the age error by applying correction factors to phenomena that heretofore could not be quantified.

Other related techniques

Phototransfer in (TL), image intensification and micro (TL) can be used as supporting techniques to the above. Their potential are presently being evaluated in conjunction mainly with (TL).

## Pressure indicators

(TL) and triboluminescence have been used in the past as pressure indicators. Both phenomena are sensitive to dislocations and their subsequent movement. The techniques can detect strain before it becomes apparent in the form of micro or macro-fracturing.

Considerations should be given to the above mentioned techniques as possible monitors for pressure or stress changes in a rock mass.

## 6- RECOMMENDATIONS

The radioactive physical techniques are the only one presently capable of directly dating secondary minerals calcite and quartz found in faults with expected ages of several tens of millions of years. It is apparent that the potential for success warrants further research which should commence in the not-to-distant future.

It is recommended that (TL), ESR and TSC measurement be made on calcite and quartz believed to be of different ages. Furthermore the results yielded by the individual radioactive damage techniques can be combined and correlated in an effort to reduce errors and attain older ages.

The problems of past or future movements along faults is crucial in selecting the site of a nuclear facility such as a power reactor or a waste repository. (TL), ESR and TSC are the only dating techniques offering potential answers or quantified answers to questions relating to the absolute age of movement along such structural lineaments.

In parallel with the above study, a literature review should be made on triboluminescence to establish the state of the art in relation to this phenomenon. This study should also attempt to indicate how it can be applied to problems of recent or future movement in faults zones i.e. fault monitoring.

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